What can we learn from experiments with high-brilliance gamma beams?

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Abstract. An overview of the main directions of present-day studies with quasimonochromatic γ beams is presented with an emphasis on the research opportunities which will be provided to the users at the Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility at Magurele near Bucharest. Experiments with γ beams at the extremes of high temperature and high neutron-to-proton ratios will be discussed. The opportunities for nuclear structure studies with γ rays with orbital angular momentum (OAM) are outlined and a few selected physics problems and classes of experiments, related to, *e.g.*, changes of photonuclear cross sections in reactions with OAM photons, as well as the possibility to address nuclear excitations with higher multipolarity are discussed. The perspectives for studies of exotic nuclei within the Gamma Factory experiment at CERN are discussed, too.

1. Introduction

In a recent review paper [1], the status of photonuclear physics research and applications was outlined. Historically, gamma-rays are one of the first probes to test the response of nuclei and observe nuclear excitations. These studies can be traced back to the 30es of the last century when such measurements provided first information about large-amplitude motion in atomic nuclei [2-4]. In the last two decades, the development of high-brilliance, quasimonochromatic gamma beams obtained via Compton back-scattering of laser light off accelerated electrons (LCB), as suggested in Refs. [5,6], increased the precision, resolution, and sensitivity of the experiments, and resulted in renewed interest to photonuclear physics. In this paper, next to the traditional approach for studies the nuclear response at the extreme of high temperature, we discuss the possibilities to produce beams of exotic nuclei through photofission, as well as possible extensions of the photonuclear studies by using vortex gamma rays which carry large orbital angular momentum.

In particular, the research opportunities which will be provided to the users at the Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility at Magurele near Bucharest are summarized, following the recently updated scientific program of the laboratory [7]. Related to studies of exotic nuclei, the expected fission-fragment yields at the Gamma Factory experiment at CERN [8] are presented.

2. Research opportunities at ELI-NP

The mission of ELI-NP is to carry out nuclear physics research with high-power lasers and high-brilliance, narrow-bandwidth, polarized γ-ray beams, a field known as nuclear photonics. The physics program, which is under preparation for the γ-beam system, includes all aspects of photonuclear studies, such as nuclear resonance fluorescence (NRF), studies of giant and pigmy resonances, photonuclear reactions and photofission, as well as numerous societal applications.

2.1. Nuclear resonance fluorescence

The interaction of photons with atomic nuclei is a very selective process due to the angular momentum selection rules. Thus, dipole and quadrupole excitations over a large range of energies are investigated in LCB NRF experiments. The quasimonochromatic γ-ray beam is tuned, such that a discrete nuclear level is excited and its decay is studied in detail. The NRF formalism and methodology are described in length in Ref. [1].

The ELIADE spectrometer [9,10], which is available at ELI-NP, is a dedicated detector system for NFR experiments with quasimonochromatic γ-ray beams. It is composed of eight segmented HPGe Clover detectors, organized in two rings, at 90° and 135° with respect to the beam axis. The detectors are placed in the horizontal and vertical planes. In addition, it is possible to add to the array large-volume $CeBr_3$ detectors at 45° with respect to the Clover detectors. The array is shown in Figure 1. The overall γ-ray efficiency of the array is about 6%, which allows measurements of γ-ray energies, intensities, angular distributions and polarization asymmetries, as well as γγ-coincidence events. Thus, it will be possible to extract from the measured spectra the γ-ray branching ratios, multipolarities, and mixing ratios, the level energies, the spins, parities and the *K* quantum numbers of the levels, their partial and total decay widths, the transition and excitation strength, and the integrated (γ,γ′) cross section.

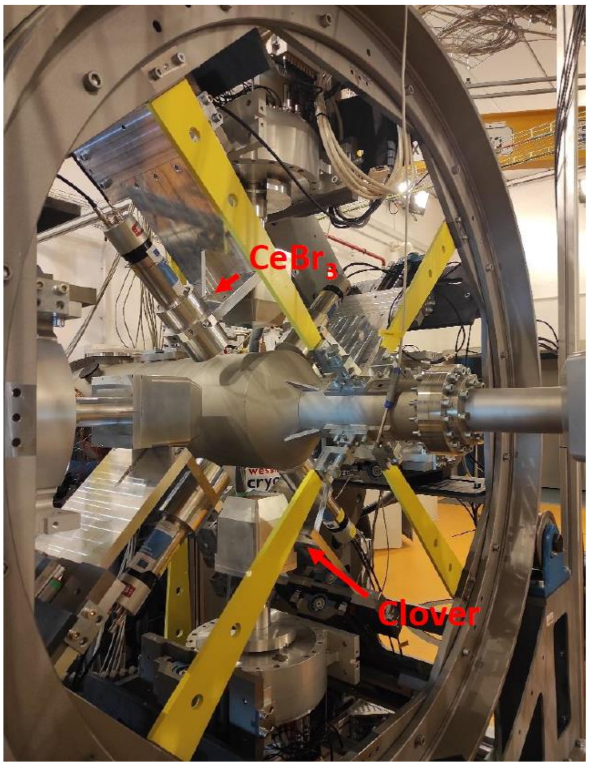

Figure 1: A photograph of the ELIADE spectrometer in one of the experimental halls of ELI-NP. The HPGe Clover and the large-volume $CeBr_3$ detectors, indicated in the figure, are facing the ELIADE reaction chamber. Photograph courtesy of Dmitry Testov.

2.2. Studies of photoneutron reactions and large-amplitude excitations

Above the particle evaporation threshold, different reaction channels open, *e.g.*, (γ,γ′), (γ,n), (γ,p), (γ,α), and (γ,f). All these will be studied at ELI-NP. The reaction mechanism is described within the Hauser-Feshbach (HF) statistical formalism of compound nuclear reaction [11]. The idea is that the probability that a specific reaction takes place is the product of the probability for formation of a compound nucleus, *i.e.*, the entrance channel, and the probability for its decay in a specific exit channel. The main assumption in the HF approach is that at high excitation energies the density of resonances and the variety of exit channels is large, which results in fluctuations in the energy dependence of the cross section. There are some problems related to the description of photonuclear reactions. In light nuclei, the density of resonances in not high enough and the model calculations poorly describe the experimental data which are also controversial. At heavier nuclei the reactions go through excitations of the giant dipole resonance (GDR). Experiments with LCB γ beams will enable detailed studies photonuclear reactions. For this purpose, a family of instruments was constructed. For example, photoneutron cross sections will be measured with the ELIGANT-TN setup [12], while the ELIGANT-GN detector array [12,13] will be used for measurements of γ rays and neutrons emitted during the de-excitation PDR or GDR states above the particle evaporation threshold.

A specific direction of research is related to the ultra-high energy cosmic rays (UHECR) propagation models, which requires a good knowledge of the total photoabsorption cross section for at least the most abundant complex nuclei in the universe, *e.g.*, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, …, ^{56}Fe. These will be studied within the PANDORA project [14]. Three facilities are involved in the project, *e.g.*, in studies at the RCNP laboratory of the University of Osaka (Japan) and iThemba LABS, Capetown (South Africa) virtual photons will be used, via Coulomb excitation induced by high-energy proton scattering, to extract the total $E1$ strength distribution up to 32 MeV and 24 MeV, respectively. Experiments at ELI-NP will make use of high-flux quasimonoenergetic real photon beams with very high-energy resolution to measure the absolute photoabsorption cross section up to 20 MeV.

2.3. Studies of charged-particle reactions

Studies of charged-particle reactions at ELI-NP address key reactions of astrophysics interest, such as the ^{16}O(γ,α)^{12}C reaction, or (γ,p) and (γ,α) reactions related to the astrophysical *p*-process. The nuclear astrophysics program at ELI-NP was recently revised and updated [7]. Two experimental setups are available for such studies, the mini-TPC detector and the ELISSA array of Si strip detectors. The mini-TPC is an active-target time projection chamber with a 256-channel electronic readout. It was developed in collaboration with the University of Warsaw. It uses gas as target and detector medium. In a photonuclear reaction, the charged-particle ejectiles ionize the gas and the produced electrons drift in external electric field towards the readout. The mini-TPC uses as three layers of gas electron multipliers (GEM) to detect the drifting electrons and a multilayer PCB readout board with three lines at 120° to each other referred as *u-v-w* readout [15]. The readout signals are used to reconstruct the reactions on event-by-event basis. A larger version of this detector, the ELITPC which will have a larger active volume and 1024-channel *u-v-w* readout is at present under construction in collaboration with the University of Warsaw.

2.4. Studies of photofission

Photofission studies at ELI-NP will address all traditional topics in the field, such as studies of sub-barrier fission. These provide information about the photofission thresholds and fission barriers. Further studies include measurements of photofission cross sections, investigation of fission fragment yields, and their angular, energy, mass, and distributions, the emission of prompt neutron and γ ray, studies of ternary fission. For the realization of these research program, two experimental setups are under construction, the ELI-BIC array of Frisch-gridded twin Bragg ionization chambers and the 4π array of thick GEM detectors, ELITHGEM [16].

3. Studies of exotic nuclei

In future, intense RIBs can be produced through photofission within the GF experiment at CERN, where very intense γ beams will be produced. The idea is to inject a beam of partially stripped ions at the SPS and utilize laser-ion collisions for the production of γ rays [8]. The resonant absorption of a laser photon is followed by an atomic transition. The energy of the emitted photon is boosted by the squared Lorentz factor of the relativistic ion beam. The cross section of this process is in the Gbarn range, *e.g.*, six orders of magnitude higher compared to the cross section of LCB, which is utilized at present day γ-beam facilities, such as ELI-NP. As a result, beams with intensities of 10^{16} photons/s can be generated. The approach for RIB production and the expected fission-fragment yields were described recently in Ref. [17]. The expected RIB yields are superior compared to other facilities which are operational or under construction worldwide.

4. Experiments with OAM photons

An important new development in the field of nuclear photonics is the production and utilization of twisted photons which carry orbital angular momentum. The generation of high-power laser pulses with OAM photons was studied extensively at ELI-NP [18]. However, the generation of high-energy OAM photons is still an open problem since it involves the transfer of orbital angular momentum in Compton backscattering. Experiments with OAM γ rays will open new opportunities in nuclear structure physics. One possibility is to study the characteristics of giant resonances of high multipolarity. Because of the validity of the long-wavelength approximation, *E*l emission dominates for most of the energy range of interest in statistical γ decay. *E*2 and *M*l are the only other multipoles whose presence might be discernible. Both the *M*1 giant resonance and the isoscalar GQR are buried under the low-energy side of the GDR. In experiments, the (γ,γ') and (γ,n) channels are considered, and the procedure to extract the strength function from the photonuclear (γ,n) data is well studied. The availability of OAM γ rays in laboratory will enable such studies. Cross section calculations with different orbital angular momentum, L, which were carried out for the *p*-process nucleus ^{96}Ru, are shown in Figure 2.

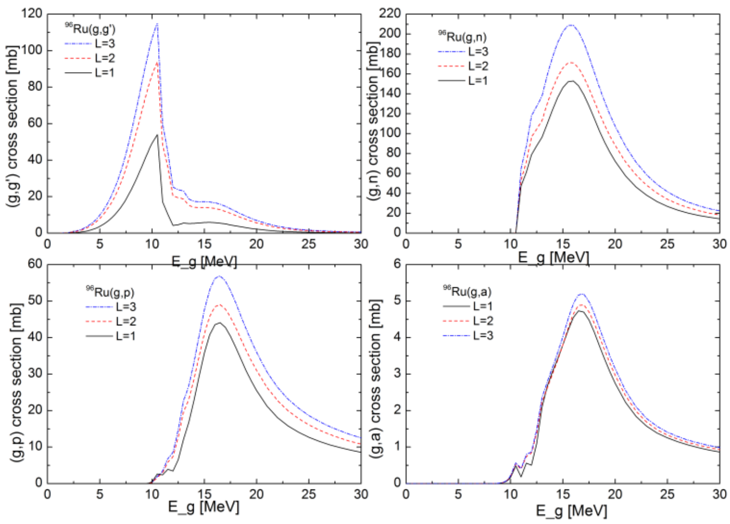

Figure 2. Cross-section calculations with different L gamma-strength functions for ^{96}Ru. Curves for L = 1,2,3 are plotted for the (γ,γ′), (γ,n), (γ,p), and (γ,α) reactiuons.

Within this approach, photons have spin angular momentum (SAM) and orbit angular momentum (OAM). Since the *E*(*M*)L strength function determines the cross section of L, we use different *E*(*M*)L strength function to calculate the cross sections of L, which are shown in Figure 2. The calculations demonstrate that the utilization of helical photons in such experiments provides a reliable experimental technique for determination of nuclear strength functions with higher multipolarities (L > 1) [19].

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